NAVAL POSTGRADUATE SCHOOL
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THESIS

DESIGN OF AN APPARATUS FOR THE STUDY OF ELECTROSTATIC EFFECTS ON GAS TURBINE FUEL SPRAYS AND COMBUSTION EFFICIENCY

by

Loren Logan Todd

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Thesis Advisor: J. Miller

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Design of an Apparatus for the Study of Electrostatic Effects on Gas Turbine Fuel Sprays and Combustion Efficiency

by

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ABSTRACT

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To demonstrate electrostatic effects on atomization, a model jet engine combustion chamber was constructed which performed effectively. However, during attempts to introduce the necessary high electric field, the flame grounded the voltage and no definitive results have been obtained.

TABLE OF CONTENTS

LIST OF FIGURES

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I. INTRODUCTION

The recent drastic increase in worldwide petroleum prices has been reflected in similar changes in the price structure of refined petroleum products. As a consequence, refiners have moved to expand the tolerances of various grades of fuels and lubricants to optimize processing yields. This has in turn lead to a tendency to supply aviation turbine fuels with increasing aromatic contents. Such blends are also characterized by lowered viscosities, increased surface tensions, and increased densities all of which alter the performance of fuel injectors, and, unavoidably, the combustor itself.

The design and construction of a jet engine fuel injector nozzle is a developmental process which seems to involve more trial and error experimental effort than scientific basis. The simplest, most effective turbine nozzles have proved to be a nonimpinging or shower-head type injector [Ref. 1]. These injectors atomize the fuel by breaking it up into tiny droplets as it is introduced into the combustion chamber. The performance of such injector nozzles depends directly on the liquid properties of the fuel. It is very difficult to design to accommodate any significant variations in these properties.

Laib [Ref. 2] has considered the suggestion that a possible solution to this problem may lie in the use of an electrostatic field (i.e., electrohydrodynamic spraying) in the

neighborhood of the injector nozzle to further control the fuel spray characteristics. He has shown that in a nonburning environment an electric charge placed in the atomization pattern of a fuel nozzle increases the fineness of the fuel droplets and alters the injection angle, although the precise physical process remains poorly understood. The resulting increase in the number of liquid fuel droplets coupled with a decrease in average diameters produces an increased vaporization surface area for the fuel. This effect may compensate sufficiently for changes in aromatic contents and may allow lesser grades of fuel to burn more efficiently at higher flame temperatures without further modification or redesign of existing fuel nozzles.

The purpose of the present work is to construct an apparatus to further the investigations of Laib and later Logan [Ref. 3] on the effects of an electrostatic field on fuel injection characteristics in a combustion environment.

II. THE ATOMIZATION PROCESS

Liquid fuel is said to be atomized when it is broken up into many small droplets of various sizes. Atomization permits a given quantity of fuel to present a large surface area which results in rapid vaporization, a prerequisite for combustion.

Most atomization processes shatter a continuous jet or sheet of liquid to produce small liquid droplets. The liquid is resolved into drops by pressurizing the fuel and forcing it through an orifice where a velocity is imparted to the fuel. When the velocity of the fuel flowing through the orifice exceeds a critical velocity (on the order of one hundred meters per second), the jet becomes unstable due to the relatively high velocity and density of the fuel. The procedure follows a process summarized by Williams [Ref. 4] which was suggested by Lord Rayleigh who found that a pressurized column of liquid is unstable if its length exceeds its circumference. These unstable columns break down into a series of monosized droplets separated by one or more satellite drops which are smaller. Due to the irregular character of the process, non-uniform threads of fuel are produced which result in a wide range of droplet diameters, usually lying between a few microns and several tens of microns [Ref. 1].

In actual practice, there are numerous ways to accomplish the process of atomization. These methods are usually grouped

according to the energy source employed to break up the liquid stream. As discussed previously, the liquid may be broken up by forcing it at high pressure through an orifice as in pressure jet atomizers, by passing a stream of gas at high velocity over a liquid surface generating waves which become extended into thin films, by impinging one liquid jet upon another, or by the use of ultrasonic waves propagated through the liquid. Hybrid atomizers may use a combination of these techniques.

For the purposes of this experiment, a simple type of pressure jet atomizer, a fuel nozzle from an Allison T-56 jet engine, was chosen. This nozzle employs parallel jets of fuel and is one of the common, nonimpinging or shower-head type injectors. An important feature of this type of pressure atomizer is that the flow rate is dependent on the pressure, following a square root law, so that for a given nozzle the following relationship holds:

$$\frac{\text{Flow Rate}}{(\text{Pressure Differential})^{1/2}} = \text{Constant (Flow Number)}$$

$$= C_f \qquad (1)$$

The resulting flow number (C_f) is a characteristic parameter of any pressure atomizer. It represents a certain critical pressure which must be attained before the atomization process can occur and also limits the lower flow rate that a particular atomizer can handle successfully [Ref. 4].

III. PHYSICAL VARIABLES AND SIZE DISTRIBUTION

As described previously, atomization processes produce a large number of small liquid droplets by shattering a continuous jet or sheet of liquid. For the pressure jet atomizer, the fuel jet becomes unstable when the surface area is increased under pressure until the jet breaks down.

The most common dimensionless group used to characterize the equilibrium droplet size is the Weber number,

$$W_e \equiv \frac{\rho_g (v_g - v_f)^2 d}{\sigma} \qquad (2)$$

where $\rho_g \equiv$ gas density, $v_g \equiv$ gas velocity, $v_f \equiv$ fluid velocity, $d \equiv$ droplet diameter and $\sigma \equiv$ liquid surface tension. For liquids, the viscosity, which is a measure of the resistance of a fluid to flow through a pipe, or here, an orifice, has a stabilizing effect which is scaled by the stability number,

$$N_s = \frac{\mu_f^2}{\rho_g d \sigma} \qquad (3)$$

For values of the stability number less than 5, the Weber number is best represented by an equation from Wallis [Ref. 5].

$$W_e = [12 + (N_s)^{0.36}] \qquad (4)$$

Wallis suggests that the presence of the liquid viscosity term in the stability criterion implies that instability initiates as a dynamic oscillation in the droplet shape. He observes further that the dynamic pressure forces then push the drop into a baglike shape at the mouth of the orifice which shatters to form one large droplet surrounded by a ring of smaller satellite droplets.

The mechanism for droplet shaping by aerodynamic forces is a complicated process which leads to a wide range of droplet sizes present in the mists formed by the atomization process. Wallis [Ref. 5] summarizes the efforts of Nukiyama and Tanasawa who investigated the relationship between the droplet size distribution generated from atomization with ambient air, subsonic gas velocities and the physical properties of the fluids. Their findings yielded an empirical equation for the average droplet radius in mists:

$$d = \frac{585}{v_o}\sqrt{\sigma/\rho_f} + 597\left(\frac{\mu_f^2}{\sigma\rho_f}\right)\left(\frac{1000\ Q_\ell}{Q_g}\right)^{1.5} \qquad (5)$$

where v_o is the initial relative velocity. A disadvantage to this equation is that it is not dimensionless and care must be taken with the units of the variables which are ρ_f, g/cm^3; v_o, m/sec; d, microns; σ, dynes/cm; μ_f, (dyne)(sec)/cm^2; and Q_ℓ/Q_g, dimensionless. This equation is the most commonly used equation for describing the performance of pressure jet atomizers. It has been proven experimentally to be most accurate when the liquid properties are in the range

$19 \leq \sigma \leq 73$ dyne cm^{-1}, $0.7 \leq \rho_\ell \leq 1.2$ gcm^{-3}, and $.005 \leq \mu_\ell \leq .5$, and where the airspeed is subsonic. The equation implies that when Q_ℓ/Q_g, the volumetric flow ratios, are very large, the mean droplet size is governed by the ratio $(\sigma/\rho_\ell)^{1/2}/v_o$, the viscosity being of little importance in this regime. However, when Q_ℓ/Q_g is small, the mean droplet size will be governed by the second term on the right-hand side of eqn (5), and both the surface tension and viscosity play an important role as stated by Hidy and Brock [Ref. 6].

The atomization process is influenced by many uncontrolled variables such as degree of turbulence, roughness, dirt deposits in the nozzles and temperature. Wallis [Ref. 5] states that these factors prevent simple droplet size predictions for practical applications. Nevertheless, one may conclude that for a given situation in which the geometry of the injector pressure is fixed, the fluid physical properties, viscosity, density, surface tension and the velocity determine droplet size distribution.

IV. ATOMIZATION IN THE PRESENCE OF AN ELECTROSTATIC FIELD

The atomization of liquid fuel produces droplets which are charged due to fluctuations in the ionic concentrations in the liquid. At the moment the droplet particle is formed, it may be highly charged with an unstable initial distribution of charges which gradually approach a stationary state due to precipitation on the particles of ions which are forming continually in the gas [Ref. 7]. The breakup and dispersion of the fuel droplets may be modified to a degree by the presence of an electrostatic field. The droplets issuing from the orifice become smaller when a high potential is applied to the droplets. When the potential reaches a few thousand volts, the droplets become smaller as they are expelled from the tip and then dispersion increases. As the electrical potential is raised, the droplets become even smaller with wider dispersion as discussed by Hidy and Brock [Ref. 6]. This phenomenon has been experimentally confirmed by Laib [Ref. 2] and also by Logan [Ref. 3]. Figures 1 and 2 are photographs of Laib's work at the Naval Postgraduate School. Figure 1 shows JP-5 sprayed at 125 psi with no electrical charge. Figure 2 shows the same fuel sprayed at the same pressure in the presence of a 26 kilovolt electric field. The wider dispersion angle is readily visible. Measurements taken by laser absorption revealed decreases in the average diameter of the fuel droplets.

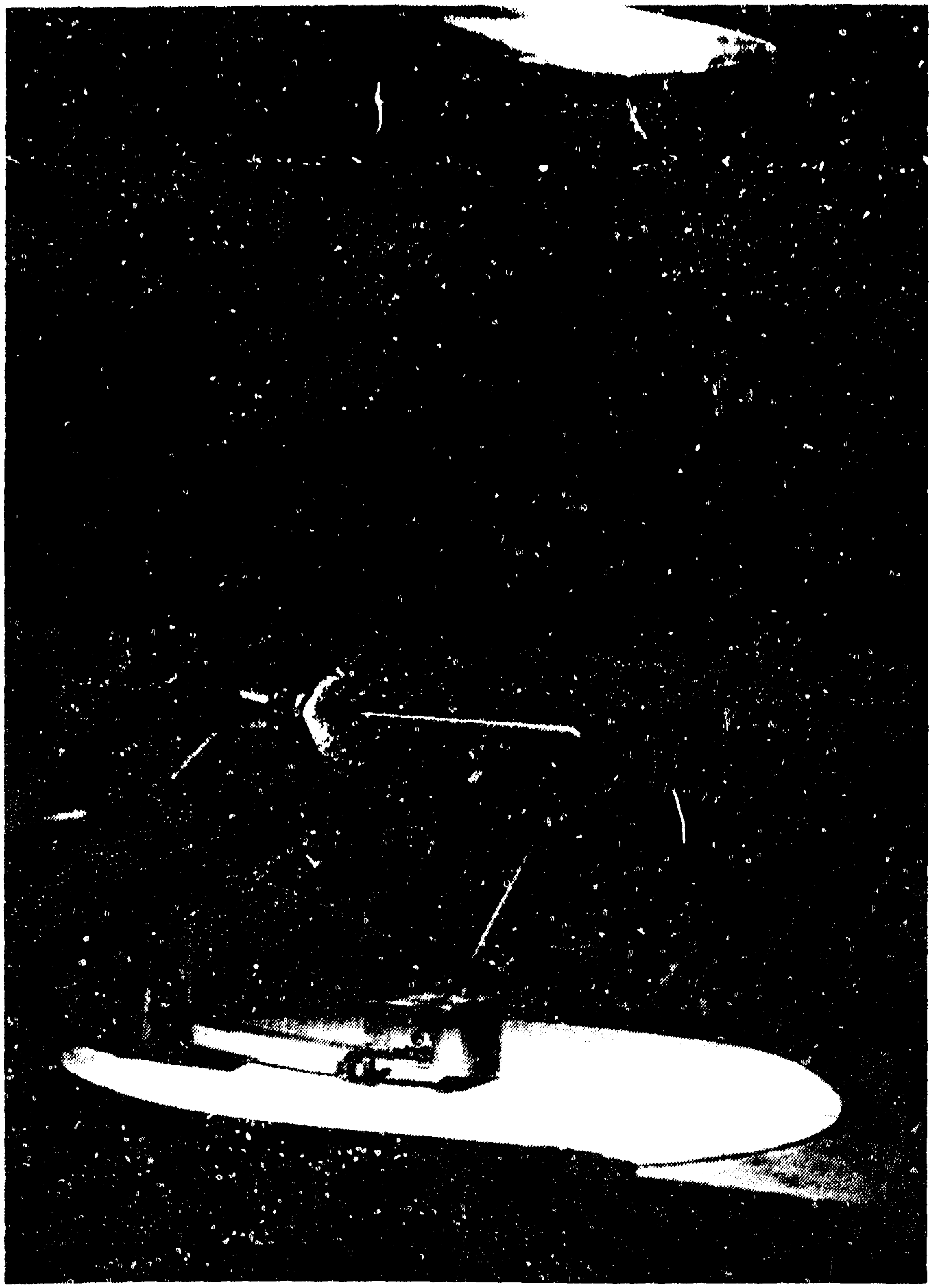

Figure 1. DISPERSION PATTERN FOR JP-5 AT 125 PSI

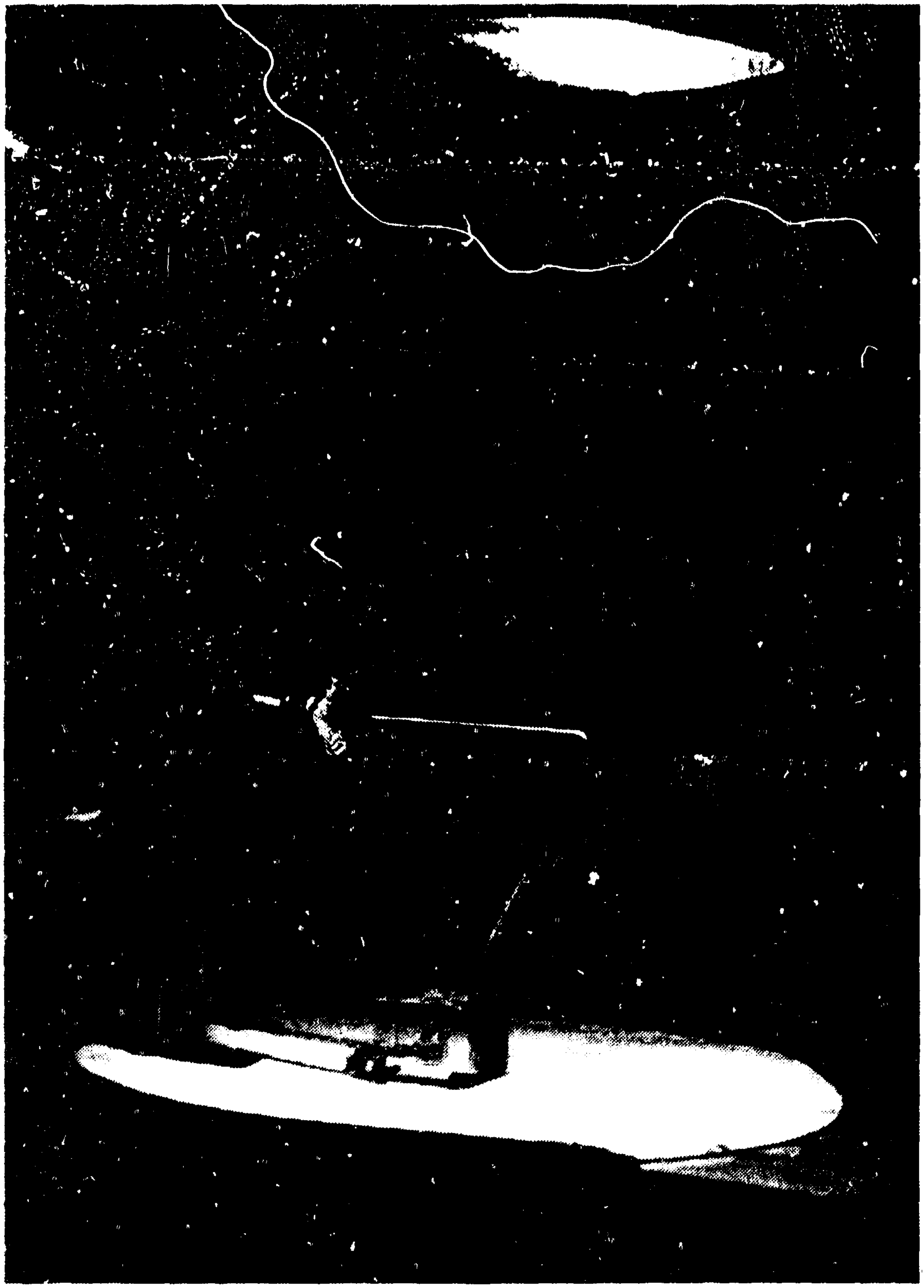

Figure 2. DISPERSION PATTERN FOR JP-5 AT 125 PSI AND 26 KV

There is no precise explanation for this process as yet. However, most investigators believe that electrostatic atomization results from a Rayleigh-like instability of the liquid thread as it issues from the orifice. Others feel that the process involves shattering of molecular bonds during high rates of unstable discharge [Ref. 6].

Experimental data have suggested that atomization is a function of conductivity with greater conductivity providing easier atomization. While there are some general guidelines for electrostatic effects on atomization, the details of the physical mechanisms are incomplete and there are presently no methods for predicting performance by the level of charge or in terms of the size distribution of the droplets formed [Ref. 6]. Nevertheless, the general effect of electrostatic fields is to reduce average droplet size.

V. THE COMBUSTION OF A FUEL DROPLET

In the combustion of liquid fuel in an oxidizing atmosphere such as air, a fuel droplet evaporates and acts as a source of vapor in the combustion chamber. Droplet combustion occurs in the form of a diffusion flame which depends on the amount of air entrained in the spray which mixes with the vaporized fuel for its efficiency. The mass burning rate $\dot{m}_f$ is related to the decrease in droplet size by a mass balance:

$$\dot{m}_f = -\frac{d}{dt}\{\frac{4}{3}\pi r_\ell^3 \rho_\ell\} \quad (6)$$

where r_ℓ is the drop radius and ρ_ℓ is the liquid density. Equation (6) may be rewritten:

$$\frac{d(d_\ell)^2}{dt} = \frac{-2\dot{m}_f}{\pi \rho_\ell r_\ell} \quad (7)$$

where d_ℓ is the diameter of the drop, equal to $2r_\ell$.

Under burning conditions, the square of the droplet diameter is a function of the burning time and is related to a proportionality constant, K, which is called the burning rate coefficient. This convenient parameter is readily obtained experimentally for each fuel and is given by

$$\frac{-d(d_\ell)^2}{dt} \equiv K \quad (8)$$

This is called the "d^2" law. By comparison of equations (7) and (8)

$$K = \frac{-2 \dot{m}_f}{\pi \rho_l r_l} \tag{9}$$

By electrostatically reducing the droplet radius, r_l, the burning rate coefficient, K, can be increased thus increasing the temperature in a combustion chamber as shown in Figure 3 taken from Williams [Ref. 4].

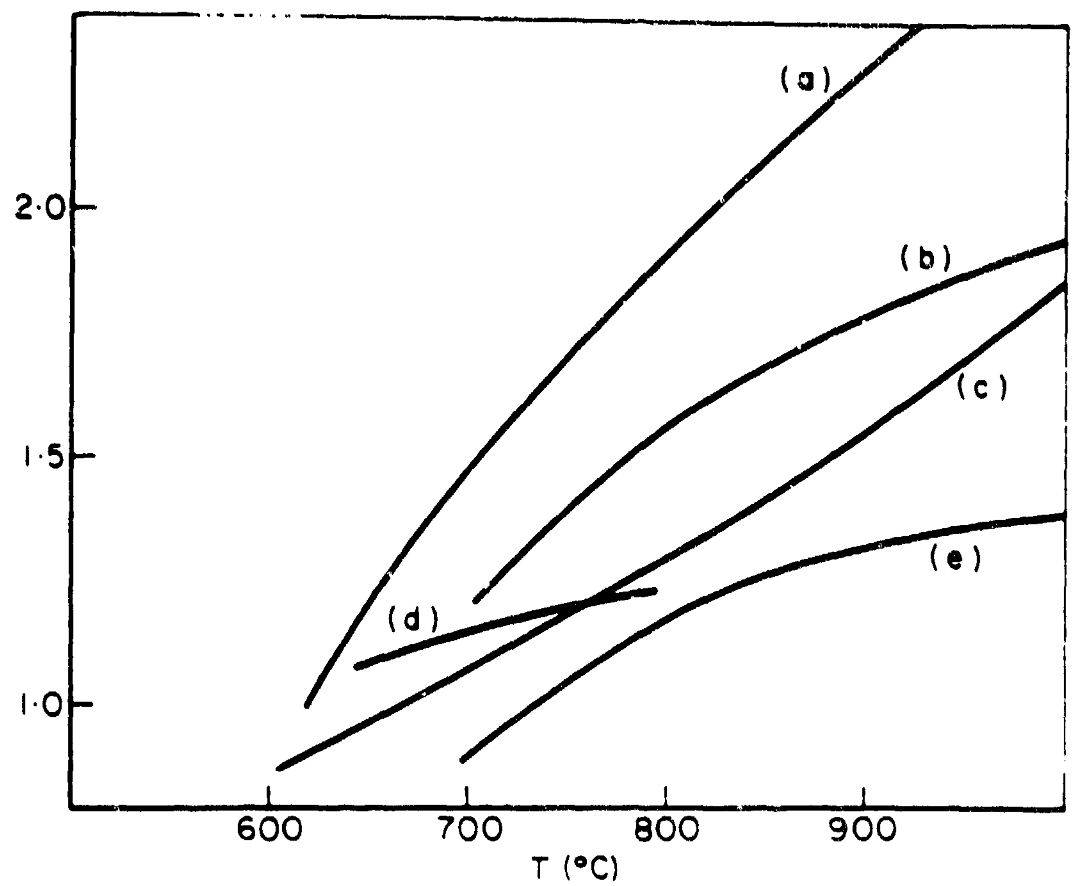

Figure 3. BURNING-RATE COEFFICIENTS OF COMPOUNDS BURNING IN AIR AT ELEVATED TEMPERATURES. (a) CETANE, (b) COMMERCIAL DIESEL FUEL, (c) AVIATION KEROSENE, (d) n- EPTANE, AND (e) BENZENE.

VI. DESCRIPTION OF THE APPARATUS

In order to test the theoretical predictions concerning the effects of electrostatic fields on combustion in gas turbine engines, an experimental combustor was designed in which each of the important parameters could be independentl controlled. An Allison T-56 jet engine combustion liner (Fig. 4) was mounted inside an eight-inch diameter stainless steel pipe (Fig. 5) using a split-ring support on the exhaust end and support of the fuel nozzle at the upstream end which corresponded to the manufacturer's original design. Both the nozzle and the igniter were taken from the Allison T-56 engine, while the exciter box or spark coil is a common aircraft part. An air-eductor exhaust pipe (Fig. 6) fitted with baffle plates cools the exhaust products by mixing with cold air and directs the stream up into the air away from personnel and structures.

The fuel supply system (Fig. 7) consists of a one-gallon capacity metal cannister which is pressurized by nitrogen. The nitrogen supply is capable of pressurizing the fuel from 75 to 350 psi which duplicates the manufacturer's design parameters for the Allison T-56 injector. The fuel cannister, nitrogen supply and regulator, and pressure relief solenoids are mounted on a common welder's cart for convenience of movement. The fuel flow is controlled by a "deadman switch" at the end of a twenty-foot extension cord. The flow of primary air is controlled by a butterfly valve bypassed with a globe

valve (Fig. 6) in the air supply line. The air supply is capable of producing liner pressure drops of 0-10 psi and can duplicate the operating ranges of all combustors presently in use. Exhaust temperature is measured by a chromel-alumel thermocouple probe mounted downstream of the exhaust nozzle (Fig. 8). Figure 8 is a schematic drawing of the combustor apparatus.

Efforts to introduce the electrostatic field into the combustion chamber were concentrated on producing a high voltage probe which could be installed without any modification to the existing major components. This initial design is shown in Figure 9. An entry point through a primary zone air port was chosen due to its accessibility and proximity to the fuel nozzle. The base for the initial probe was machined from an aircraft spark plug. The electrode was secured to the plug using Sauereisen cement on the combustion zone side and epoxy glue externally. This probe was capable of maintaining charges in the desired 0-30 kv range in air but grounded out when exposed to the relatively high conductivity of the combustion flame. Attempts to insulate this design were unsuccessful largely due to the cumbersome geometry of the electrode tip.

A second generation design shown in Figure 10 evolved; it employs the same air port. The second design used the same spark plug base but eliminated the 90 degree bend in the electrode by inserting it at an angle. This electrode was more

easily insulated using high temperature ceramic tubing but again did not sustain the high voltage when exposed to flame. Final efforts at a probe shown in Figure 11 included blowing air through an annulus in the ceramic insulator in an effort to extinguish the combustion flame locally in the area of the electrode tip. Insufficient mass flow through the electrode appears to have prevented this flow from totally extinguishing the flame in the neighborhood of the probe. Moreover, a flame-holder effect at the probe itself seems to be present. The lightly colored area on the tip of the probe shown in Figure 11 illustrates the area in which the flameholder effect produces localized combustion.

VII. RESULTS

A working apparatus was successfully designed and constructed which effectively models a T-56 combustion chamber. The burner is capable of burning a wide range of turbine fuels including JP-4, JP-5, and diesel oil with complete and independent control over the air and fuel flow rates.

Additionally, attempts of limited success were made to fabricate a satisfactory high voltage probe which would introduce an electric charge on the fuel as it was atomized by the nozzle. The performance of the probe in the flame, however, has serious limitations because of the flame conductivity.

VIII. CONCLUSIONS

Although an apparatus was successfully designed to adequately simulate the combustion chamber of a gas turbine engine, it was not possible to experimentally verify the theoretical effects of an electrostatic field on injection spray characteristics which were previously confirmed in a non-combusting flow. The difficulty which precludes success results from the high conductivity of the combustion products. These products create a low resistance path to ground potential and effectively short circuit the high voltage probe. This difficulty can likely be overcome by a probe design which embodies more adequate electrical insulation, and perhaps cooling where the probe passes through high temperature combustion products, or one which completely avoids such high conductivity regions. This, however, lies beyond the scope of the present work.

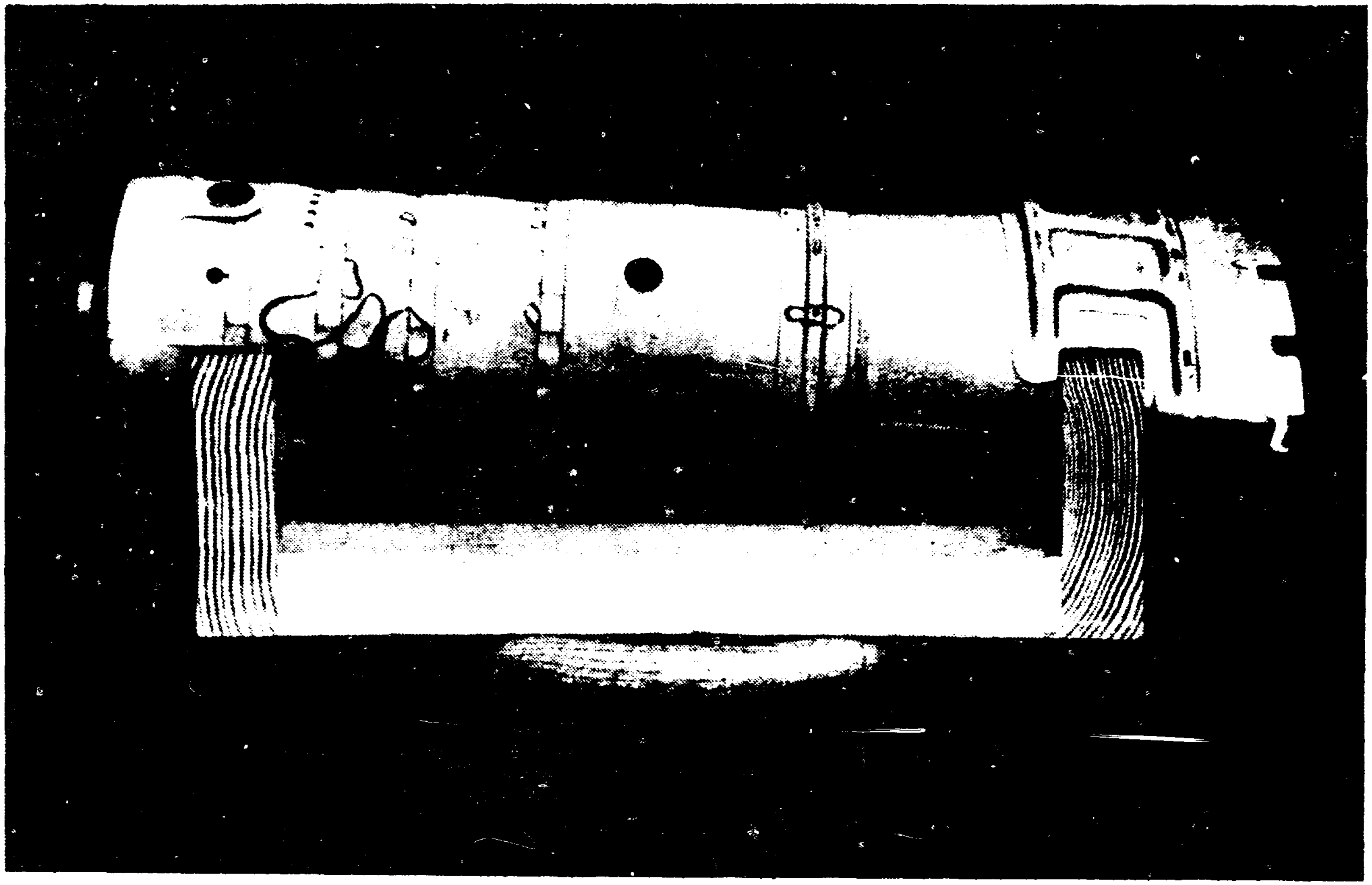

Figure 4. T-56 ENGINE COMBUSTION LINER

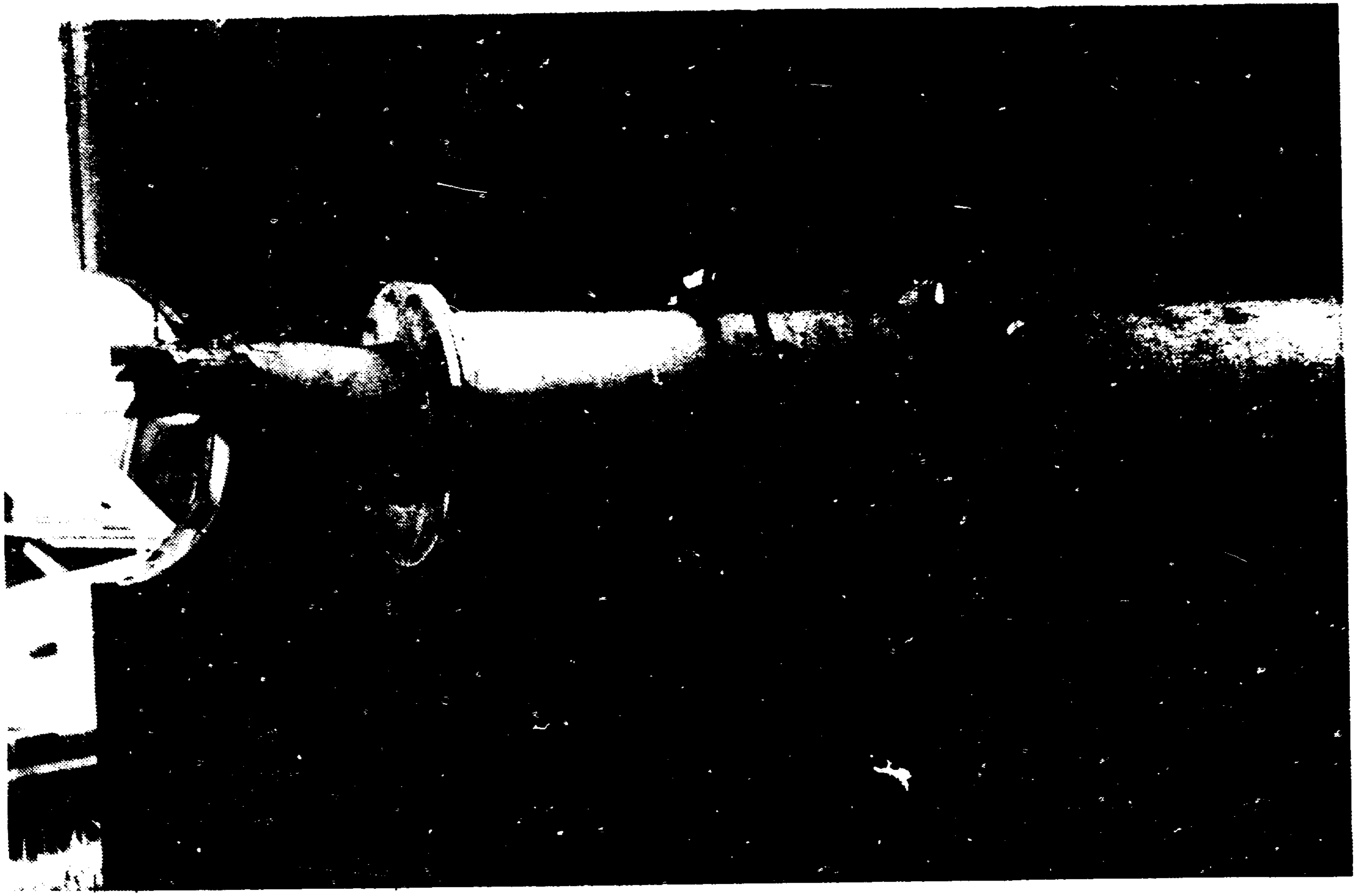

Figure 5. PIPE LINER, IGNITER, ELECTRODE, FUEL LINE

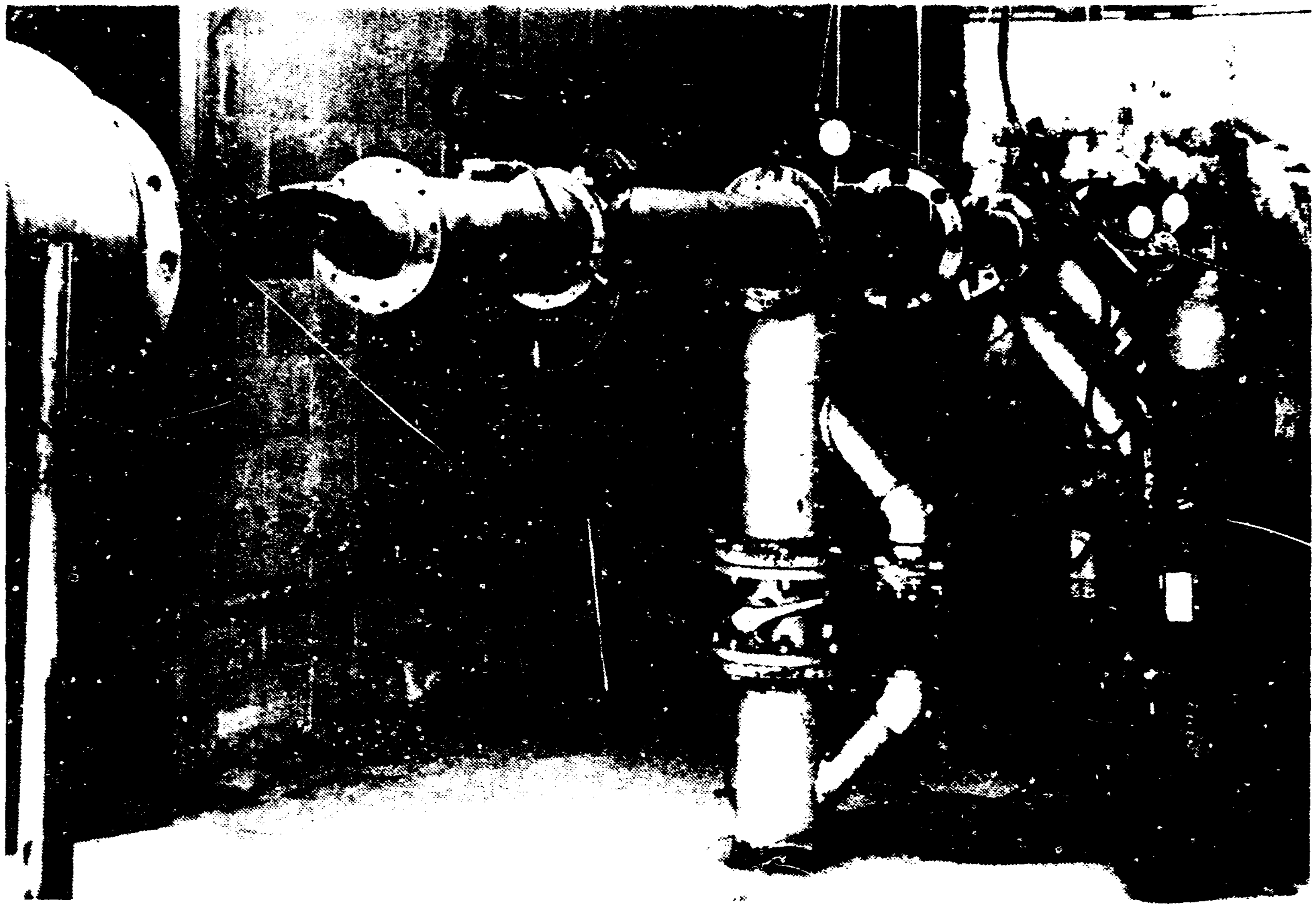

Figure 6. TEST APPARATUS WITH EDUCTOR EXHAUST PIPE

Figure 7. FUEL SUPPLY SYSTEM

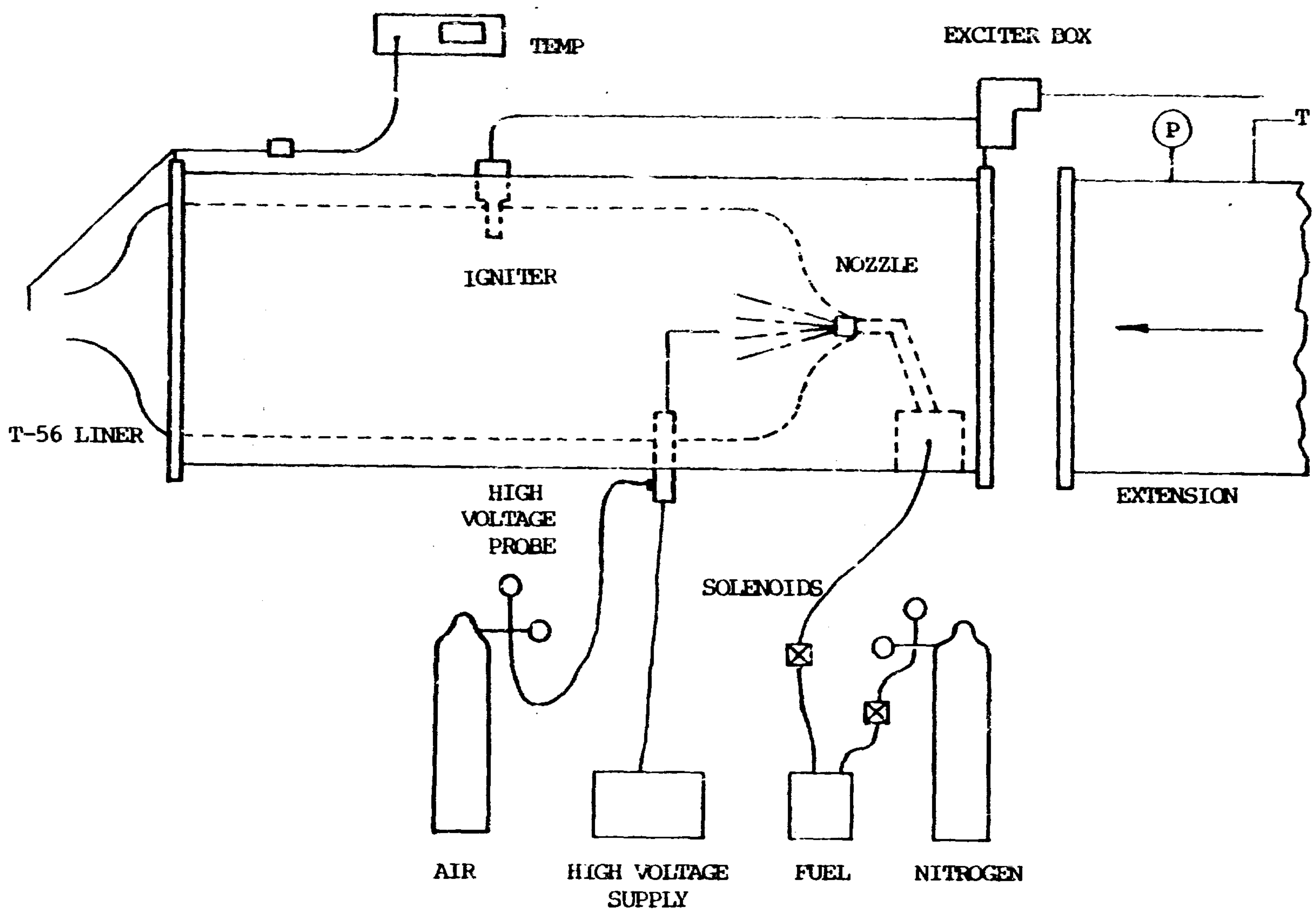

Figure 8. SCHEMATIC DRAWING OF COMBUSTOR APPARATUS

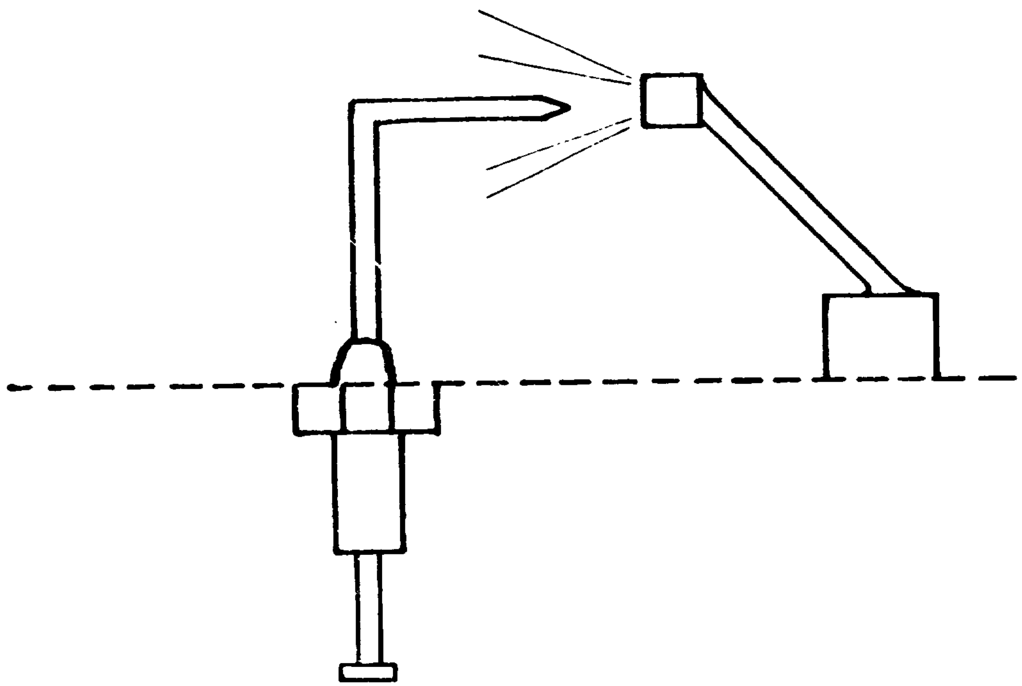

Figure 9. INITIAL VOLTAGE PROBE

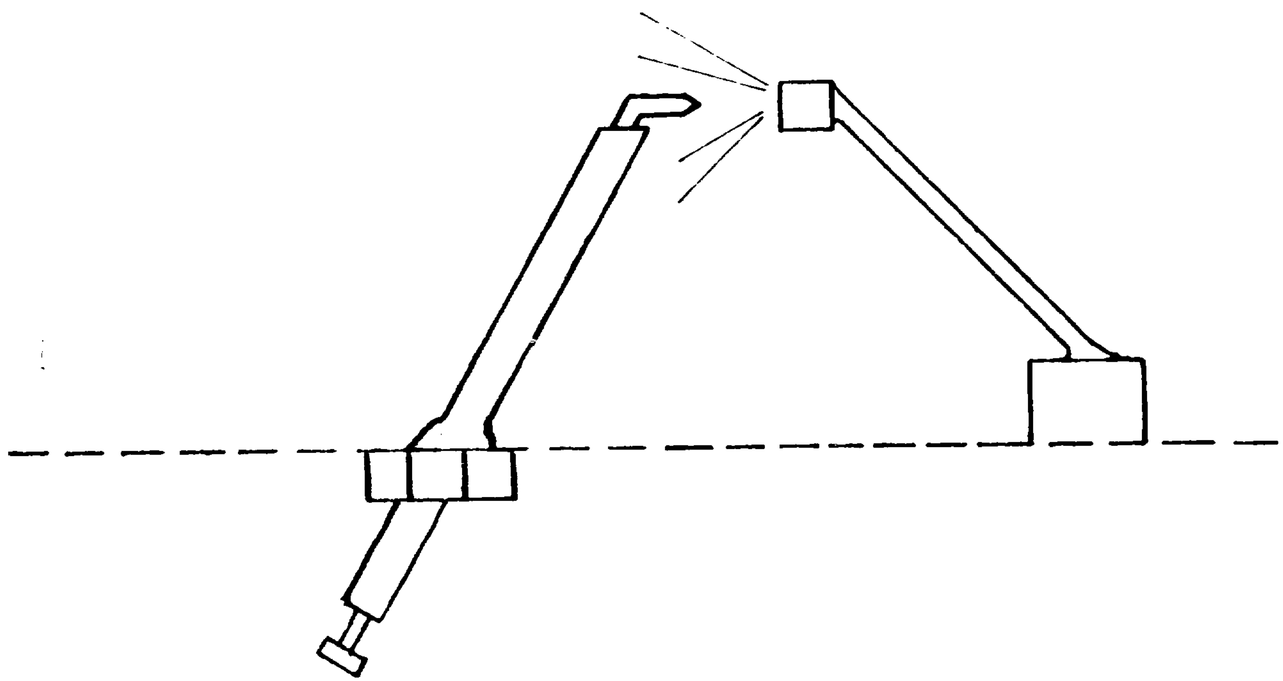

Figure 10. SECOND GENERATION VOLTAGE PROBE

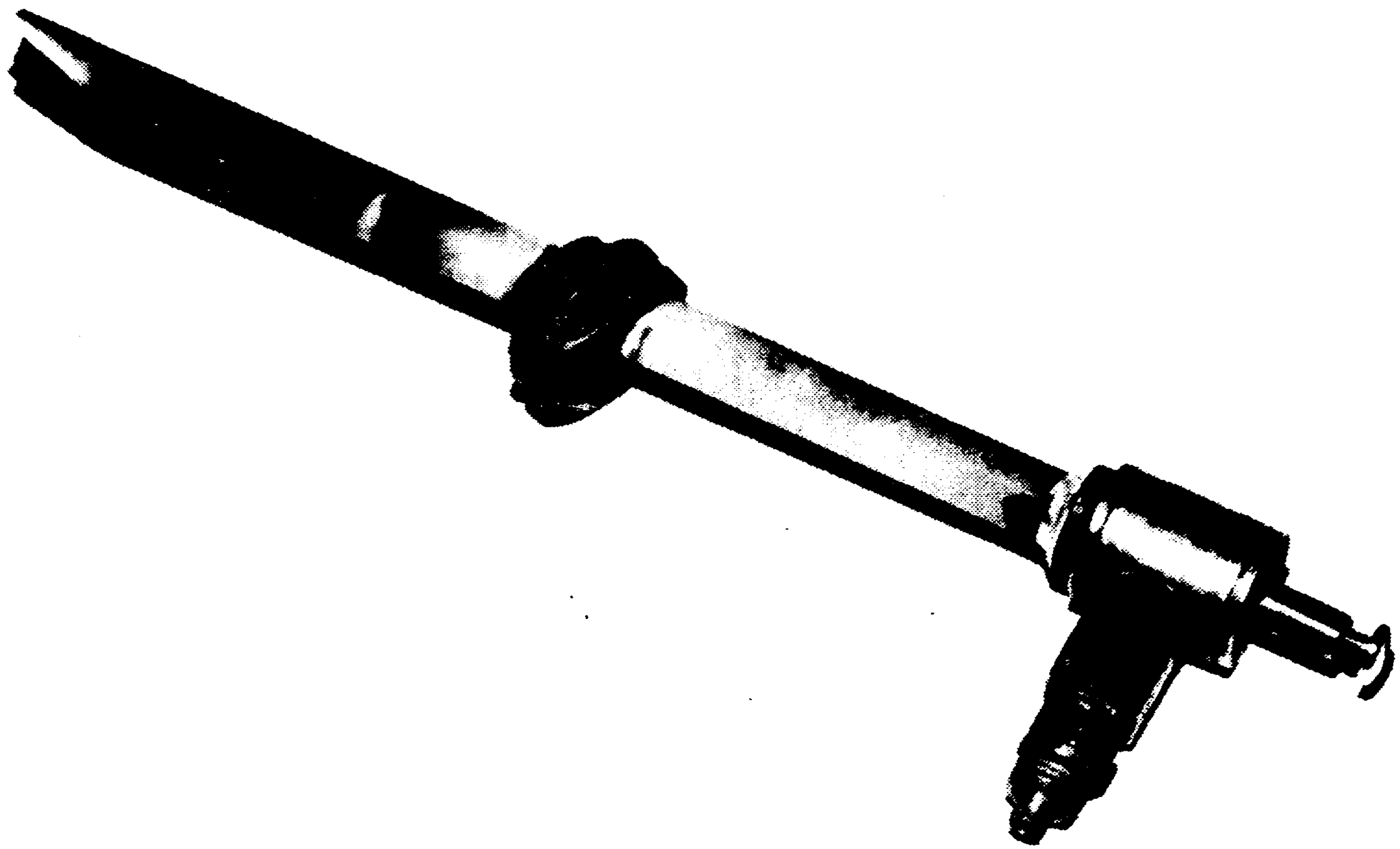

Figure 11. SECOND GENERATION VOLTAGE PROBE WITH BLOWING ATTACHMENT

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